Influence of the Soil Thermal Non-Homogeneity on the Cable Current Ampacity

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Abstract – **Determination of the thermal rated current of cable is usually made on the assumption that soil is homogeneous in thermal sense. However, rout of long cables sometimes passes through soils with different thermal characteristics, or one part of the cable passes through a duct. All these practical cases, as a rule, can be reduced to a few characteristic ones. The relations for temperature distribution along the cable, for these characteristic cases, are developed in this paper. The influence of the soil thermal non-homogeneity on the cable current ampacity is then determined using developed relations. The analysis is made for the cable XHE48-A 1x1000/95 mm2 64/100 kV.**

Keywords – **cable, current ampacity, soil, drying-out.**

I. Introduction

In order to determine the thermal current ampacity of the cables laid in the ground, general assumption is that the soil is homogeneous in thermal sense. However, the route of long cables may sometimes pass through the soil of different structure and thus different thermal characteristics. There are also examples of the cables placed in pipes and ducts.

In such cases even when the soil is thermally homogeneous, the conditions of cable heat dissipation are changing. The question here is how big is the real influence of soil thermal non-homogeneity on the cable ampacity; for example, short part of the cable passing below a concrete or asphalt surface.

That is why this paper is presenting two general cases, which resemble problems found in practice. If we analyze elementary part of cable conductor and its heat dissipation, following equations will define temperature rise along the conductor.

II. Distribution of temperarature along route of the cable

The analysis of thermal non-homogeneity along the rout of cables on thermal current-carrying capacity is based on the temperature rise along the conductor. Fig. 1 is showing the elementary part of conductor marked as *dx*, with transmitted powers P_1 and P_2, heat conductivity of conductor λ, temperature θ and cross-sectional area S.

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$$P_1 = -\lambda S \frac{\partial \theta}{\partial x} , \quad (1)$$

$$P_2 = -\lambda S \frac{\partial}{\partial x}(\theta + \frac{\partial \theta}{\partial x} dx) . \quad (2)$$

P_3 is dissipated heat of elementary part of the conductor, caused by current under normal conditions of exploitation. Beside dissipated heat of the conductor, important parts are also the losses generated in metal sheath. Therefore dissipated heat is calculated as:

$$P_3 = R'_{20}(1 + \alpha(\theta - 20))I^2 dx , \quad (3)$$

where R'_{20} is effective resistance of cable at 20°C, and α is temperature coefficient for the electrical resistance.

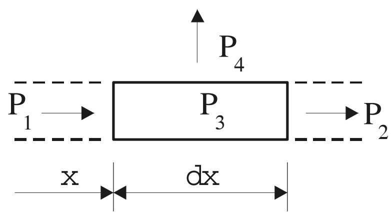

Fig. 1. Elementary part of the conductor

Part of dissipated heat, conducted from the surface of elementary part of the conductor through the cable insulation and surrounding soil, is marked as P_4 in Fig. 1. If we ignore drying-out effect of the soil, conducted power P_4 will be:

$$P_4 = \frac{\theta - (\theta_E + P'_d(T'_{Kd} + T'_4))}{T'_{Ki} + T'_E} dx = \frac{\theta - (\theta_E + \Delta\theta_d)}{T'_{Ki} + T'_E} dx , \quad (4)$$

where: θ_E is temperature of soil with cables not loaded, P'_d is dielectric loss of a cable, T'_{Kd} is fictitious thermal resistance of a cable when considering the dielectric losses, T'_{Ki} is fictitious thermal resistance of a cable when considering the ohmic losses, T'_E is thermal resistance of the ground, $\Delta\theta_d$ is temperature rise of a conductor above ambient due to dielectric losses.

All thermal resistances and powers in Eq. (4) are per unit length. Estimation of thermal resistances is explained in [3,4]. Load has no influence on dielectric losses (eventual variation of voltage is ignored), so temperature rise due to dielectric losses is constant. Power of dielectric losses can be ignored for low-voltage cables.

$$P_4 = \frac{\theta - (\theta_E + \Delta\theta_d) + \frac{\rho_x - \rho_E}{\rho_E} \cdot \Delta\theta_x}{T'_{Ki} + T'_x} dx , \quad (5)$$

where: ρ_E is thermal resistivity of the moist soil, i.e. the moist area, ρ_x is thermal resistivity of the dried-out soil, i.e. the dry area, T'_x is thermal resistance of the dried-out soil, and $\Delta\theta_x$ is limiting temperature rise of the boundary isotherm above ground temperature.

The power balance in operating conditions for the elementary part of the cable is:

$$P_1 + P_3 = P_2 + P_4 \; . \tag{6}$$

If we replace equations for the powers P_1, P_2, P_3 and P_4 into Eq. (6), when the drying-out effect is ignored, we will come up with the following partial differential equation:

$$\frac{\partial^2\theta}{\partial x^2} - \frac{1-(T'_{Ki}+T'_E)\alpha R'_{20} I^2}{\lambda \cdot S(T'_{Ki}+T'_E)}\theta = \\ = \frac{(T'_{Ki}+T'_E)\cdot R'_{20}\cdot(1-20\alpha)I^2 + (\theta_E + \Delta\theta_d)}{\lambda \cdot S(T'_{Ki}+T'_E)} \; . \tag{7}$$

The solution of Eq. (7) has following form:

$$\theta = \theta_{st} + A\cdot e^{ax} + B\cdot e^{-ax} \; , \tag{8}$$

$$\theta_{st} = \frac{(T'_{Ki}+T'_E)\cdot R'_{20}\cdot(1-20\alpha)I^2 + (\theta_E+\Delta\theta_d)}{1-(T'_{Ki}+T'_E)\alpha R'_{20} I^2} \; , \tag{9}$$

$$a = \sqrt{\frac{1-(T'_{Ki}+T'_E)\alpha R'_{20} I^2}{\lambda\cdot S(T'_{Ki}+T'_E)}} \; , \tag{10}$$

where A and B are appropriate constants.

If drying-out effect of the soil is significant, the steady state temperature is:

$$\theta_{st} = \frac{1}{1-(T'_{Ki}+T'_E)\alpha R'_{20} I^2}\cdot\Big[(\theta_E+\Delta\theta_d) \\ +(T'_{Ki}+T'_E)\cdot R'_{20}\cdot(1-20\alpha)I^2 - \frac{\rho_x-\rho_E}{\rho_E}\Delta\theta_x\Big] \; . \tag{11}$$

Factors A and B will be calculated from boundary conditions, for every practical example. We will analyze two characteristic cases shown on Figs. 2 and 3.

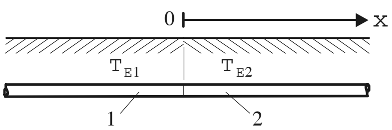

Fig. 2. Example with two different types of soil

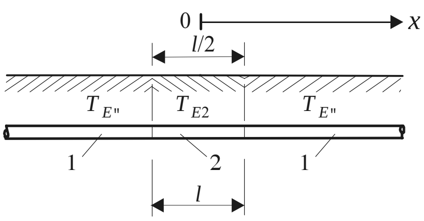

Fig. 3. Thermal non-homogeneity of soil at one part of the cable

According to Eq. (8) for the example shown on Fig. 2 we can calculate temperature distribution along parts 1 and 2:

$$\theta_1 = \theta_{st1} + A_1 e^{a_1 x} + B_1 e^{-a_1 x}, \quad x \leqslant 0 \; , \tag{12}$$

$$\theta_2 = \theta_{st2} + A_2 e^{a_2 x} + B_2 e^{-a_2 x}, \quad x \geqslant 0 \; . \tag{13}$$

If we analyze the two previous relations, temperature will increase indefinitely when $x \to \infty$. Since that is impossible, it is obvious that the factors A_2 and B_1 must equal zero. Factors A_1 and B_2 are determined for x=0:

$$\theta_1\,(x=0) = \theta_2\,(x=0) \; , \qquad \left.\frac{\partial\theta_1}{\partial x}\right|_{x=0} = \left.\frac{\partial\theta_2}{\partial x}\right|_{x=0} \; ,$$

so the factors A_1 and B_2 are:

$$A_1 = \frac{a_2}{a_1+a_2}\,(\theta_{st2}-\theta_{st1}) \; , \tag{14}$$

$$B_2 = -\frac{a_1}{a_1+a_2}\,(\theta_{st2}-\theta_{st1}) \; . \tag{15}$$

Therefore, the temperature distribution along the cable for example shown on Fig. 2 will be:

$$\theta_1 = \theta_{st1} + \frac{a_2}{a_1+a_2}\,(\theta_{st2}-\theta_{st1})\,e^{a_1 x} \; , \quad x \leqslant 0 \; , \tag{16}$$

$$\theta_2 = \theta_{st2} - \frac{a_1}{a_1+a_2}\,(\theta_{st2}-\theta_{st1})\,e^{-a_2 x} \; , \quad x \geqslant 0. \tag{17}$$

For the example on Fig. 3 equation for the temperature distribution is:

$$\theta_1 = \theta_{st1} + \\ + \frac{a_2}{a_1}\frac{(\theta_{st2}-\theta_{st1})\,sh\left(a_2\frac{\ell}{2}\right)}{ch\left(a_2\frac{\ell}{2}\right)+\frac{a_2}{a_1}sh\left(a_2\frac{\ell}{2}\right)} e^{\left(-a_1\left(x-\frac{\ell}{2}\right)\right)} \; , \tag{18}$$

when $x \geqslant l/2$, and

$$\theta_2 = \theta_{st2} - \frac{\theta_{st2}-\theta_{st1}}{ch\left(a_2\frac{\ell}{2}\right)+\frac{a_2}{a_1}sh\left(a_2\frac{\ell}{2}\right)} ch\,(a_2 x) \tag{19}$$

when $0 \leqslant x \leqslant l/2$.

III. Current Ampacity Factor

Magnitude of the thermal current is determined by permissible operating temperature of conductor θ_c. Considering the relation for steady state temperature Eq. (9), for $\theta_{st} = \theta_c$, current ampacity on the parts 1 and 2 as shown on Fig. 1 will be:

$$I_{1\,(2)} = \sqrt{\frac{\theta_c - \theta_{E1\,(2)} - \Delta\theta_{d1\,(2)}}{(T'_{Ki}+T'_{E1\,(2)})R'_{20}\,(1+\alpha(\theta_c-20))}} \; . \tag{20}$$

It is obvious that for the load capacity we will chose the smaller value. Ratio of these two currents gives us current ampacity factor for the thermal non-homogeneity along route of the cable, and practically points out the current efficiency on the part of the cable under the good thermal conditions:

$$f_i = \frac{I_2}{I_1} = \sqrt{\frac{\theta_c-\theta_{E2}-\Delta\theta_{d2}}{\theta_c-\theta_{E1}-\Delta\theta_{d1}}\frac{T'_{Ki}+T'_{E1}}{T'_{Ki}+T'_{E2}}} \; . \tag{21}$$

Regarding Eqs. (18) and (19) for current ampacity factor of the example shown on Fig. 3 we will have:

$$f_i = \sqrt{\frac{b - \sqrt{b^2 - ac}}{\alpha(\theta_c - \theta_{E1} - \Delta\theta_{d1})(T'_{Ki} + T'_{E2})}} \,, \qquad (22)$$

where:

$$\begin{aligned} a =& \alpha \ (1 + \alpha \ (\theta_c - 20)) \ (T'_{Ki} + T'_{E1}) \ (T'_{Ki} + T'_{E2}) \ , \\ b =& \frac{1}{2} \left[\alpha \left(\theta_c - \theta_{E2} - \Delta\theta_{d2} \right) \left(T'_{Ki} + T'_{E1} \right) \right. \\ & + \left(1 + \alpha \left(\theta_c - 20 \right) \right) \left(T'_{Ki} + T'_{E2} \right) \\ & - p \left(1 + \alpha \left(\theta_{E1} + \Delta\theta_{d1} - 20 \right) \right) \left(T'_{Ki} + T'_{E2} \right) \\ & \left. - \ p \left(1 + \alpha \left(\theta_{E2} + \Delta\theta_{d2} - 20 \right) \right) \left(T'_{Ki} + T'_{E1} \right) \right] , \end{aligned}$$

$$c = \theta_c - \theta_{E2} - \Delta\theta_{d2} + p \ (\theta_{E2} + \Delta\theta_{d2} - \theta_{E1} - \Delta\theta_{d1}) \ ,$$

$$p = \frac{1}{ch\left(a_2 \frac{\ell}{2}\right) + \frac{a_2}{a_1} sh\left(a_2 \frac{\ell}{2}\right)}.$$

IV. Test Example

The influence of thermal non-homogeneity is based on analysis of current load of three single-core cables XHE 48-A 11000/95 mm ^{2} 110 kV in 3-phased system bunched. Thermally permissible current for these cables, when thermal resistivity is $\rho_{E1} = 1.2$ Km/W and temperature of referent ground $\theta_E = 20$°C is $I = 785$ A [6]. Supposing the cable is long enough (according to [6], the length of such cable in Belgrade is approximately 9 km), and that one part of the cable with the length of $l = 10$ m, placed around the central point of rout, is laid in the ground of thermal resistivity $\rho_{E2} = 2$ Km/W. This example is presented on Fig. 3.

According to available information of the cable presented in [6], we can easily define data needed for this analysis: R'_{20}=39.2 $\mu\Omega$/m, $T'_{Ki} = 0.344$ Km/W, T'_{Kd}=0.25 Km/W, P'_d = 0.23 W/m, T'_{E1}=1.9 Km/W, T'_{E2}=2 Km/W. Temperature coefficient for electrical resistance of aluminum conductor at 20°C is $\alpha = 0.00403\,\mathrm{K}^{-1}$, thermal conductivity factor is $\lambda = 230$ W/Km and temperature of referent ground in both sections of cable is $\theta_{E1} = \theta_{E2} = 20$°C.

If load capacity is I=785 A for such defined conditions, we will have steady state temperatures $\theta_1 = 90$°C and θ_2 = 149.6°C, while coefficient a will be a_1=1.23 m^{-1} and a_2=0.903 m^{-1}. If coordinate system is as shown on Fig. 3, for the temperature distribution along the cable, we will have:

$$\theta_1 = 90 + 25.23\, e^{-1.23(x-5)} \ , \ x \geqslant 5\,\mathrm{m},$$
$$\theta_2 = 149.6 - 0.752\, ch(0.903 \cdot x) \ , \ 0 \leqslant x \leqslant 5\,\mathrm{m},$$

where x is expressed in meters (m), and temperature in °C.

Fig. 4 illustrates temperature distribution on the part of conductor defined by previous equations. We can notice that axial heat conduction practically does not influence temperature rise of thermally critical point. The temperatures θ_{st1} and θ_{st2}, reach their values yet at distance 2 to 3 m from the place of discontinuity. These distances are even lesser for medium-voltage cables. This brings us to conclusion that the limit for current capacity of the cable, regardless of its length, is determined at the part of the route where thermal conditions are not so good as at the rest of the cable.

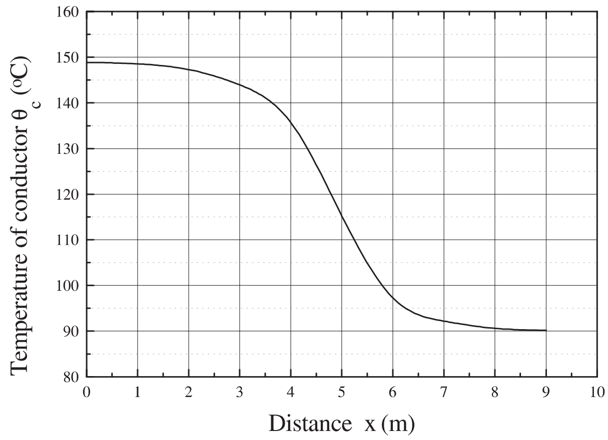

Fig. 4. Temperature distribution along the cable according to the Eqs. (18) and (19)

The fact that discontinuity effect has influence only on a short part of the cable, we can use Eqs. (16) and (17) instead of Eqs. (18) and (19), which are easier to analyze. Considering these equations, we can place origin of the axis system at the point of discontinuity (which is displaced for $l/2 = 5$ m in direction of x-axis), and temperature rise along the parts 1 and 2 (considering that positive part of x-axis is marked as 1) we will have:

$$\theta_1 = 90 + 25.23\, e^{-1.23\, x}, \ x \geqslant 0 \ ,$$
$$\theta_1 = 149.6 - 34.37\, e^{0.903\, x}, \ x \leqslant 0 \ .$$

Temperature distribution for this example is shown on Fig. 5. If we compare graphs on Figs. 4 and 5 we can see that basically it is the same curve with different origins of axes system. This points out that even when there are several points of discontinuity, temperature rise can be expressed by Eqs. (16) and (17). The only thing that must be arranged is to place origin of axis system in the point of discontinuity.

From the previous statement for current ampacity factor, we can use Eq. (21), which is simpler than Eq. (22). Using

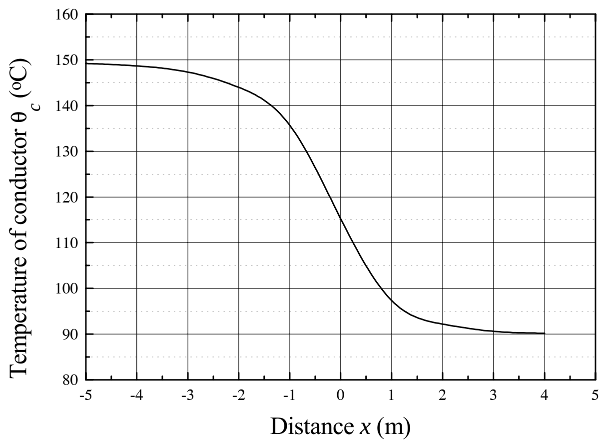

Fig. 5. Temperature distribution along the cable according to the Eqs. (16) and (17)

Eq. (21) for this example, current ampacity factor will be $f_i = 0.797$, and if we use Eq. (22) we will have $f_i = 0.796$. It is obvious that the difference is insignificant, and the usage of Eqs. (16), (17) and (21) is justified.

Existance of the one short part of rout where thermal resistivity of the soil increases from 1.2 Km/W to 2 Km/W leads to decrement of current ampacity for more than 20%. Therefore, instead of 785 A for permissible current we will have 625 A, and most of the cable will be inefficiently exploited. According to these facts we can realize the significance of the special bedding mixtures used in similar situations.

V. Conclusion

This paper presents mathematical model for analysis of soil non-homogeneity on current ampacity of the cables. The analysis of the two general cases, which resemble problems found in practice, clearly points out that the easier method of calculation is efficient enough. Mathematical model based on the less complicated example is appropriate for calculations even when cable has several points of thermal discontinuity.

This analysis proves that thermal non-homogeneity of the soil has significant influence on a cable load capacity. It is obvious that the increase of soil thermal resistivity has essential influence on permissible current. That is why we should know thermal characteristics of the ground before laying a cable. For better current exploitation, in places that are thermally critical, we should use special cable bedding mixtures.

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